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A MUNICIPAL LANDFILL COVER WITH A PAPER SLUDGE BARRIER LAYER

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ABSTRACT

The Corinth landfill closure project was the first in New York State to use paper sludge as alternative barrier layer material in a landfill cap. The use of paper mill sludge in the cap reduced cost relative to a conventional clay or geomembrane cap system. The beneficial reuse of the paper sludge also saved landfill space.

To demonstrate the feasibility of using paper sludge as barrier layer material, extensive research was conducted to evaluate the physical properties of the sludge, primarily hydraulic conductivity. Centrifuge model tests were conducted to simulate infiltration through the cap over a 30 year period. Centrifuge modeling was used in lieu of field test sections, at significant saving in time and cost.

Paper sludge behaves similar to a highly organic peat soil. It has high water content, is highly compressible, and its hydraulic conductivity is a function of the organic content of the material. These characteristics impacted cap design and construction methods.

This paper summarizes the research performed for this project, including centrifuge testing. Cap design is discussed, taking into consideration the properties of the sludge. Construction of the landfill cap is described, including construction techniques and QA/QC protocol. Barrier layer QA/QC data are summarized. Physical properties of the paper sludge are emphasized herein; analytical data are not included.

KEY WORDS

Paper sludge, landfill cap, beneficial reuse, centrifuge modeling, hydraulic conductivity

INTRODUCTION

The Town of Corinth, New York, municipal landfill was closed in 1991 and was capped in 1994 to 1995 in accordance with New York State Department of Environmental Conservation (NYSDEC) regulations in effect May 1991. Conventional capping systems in New York State under these regulations normally include either a geomembrane barrier or a 0.45m (18-inch) clay barrier layer having a hydraulic conductivity less than 1×10^{-7} cm/s. To reduce capping costs, the Town constructed an alternative capping system using paper sludge from the International Paper Company (IP) Hudson River Mill in Corinth as barrier layer material. In addition to reducing costs, this unconventional capping system provided a beneficial reuse for IP's sludge that would otherwise have been landfilled at the Mill.

Extensive studies were completed to evaluate the feasibility of using IP paper sludge in lieu of conventional clay in the barrier layer. The overall intent of the studies was to establish whether the sludge will provide a long term barrier with a hydraulic conductivity less than 1×10^{-7} cm/s and to verify that use of the paper sludge barrier layer will provide long term improvement of site groundwater comparable to improvements anticipated with a conventional cap. These issues were NYSDEC's primary concerns. Based on the studies, NYSDEC approved the use of IP sludge as barrier layer material for capping the Town of

Corinth's 5.3 ha (13 acre) landfill as a demonstration project, the first in New York State.

This paper summarizes the geotechnical properties of IP's paper sludge obtained from the feasibility studies, primarily hydraulic conductivity. It includes the effects of freeze-thaw and biologic degradation on sludge hydraulic conductivity. Design and construction considerations for a landfill cover using paper sludge as the barrier layer are discussed. Construction quality assurance/quality control (QA/QC) data are also included.

Analytical testing of IP sludge was performed for the feasibility study, including analysis of runthrough collected from centrifuge model tests intended to simulate cap performance over a 30 year life. Analytical data, however, are not included herein.

PREVIOUS STUDIES

Numerous studies have been conducted to find alternative uses for paper mill sludges, including landfill cover systems (NCASI, 1984; NCASI, 1985; NCASI, 1989; NCASI, 1990; Swann, 1991; NCASI, 1992a; NCASI, 1992b; Kraus and Benson, 1994; Moo-Young, 1995; Moo-Young and Zimmie, 1995a; Moo-Young and Zimmie, 1995b; Moo-Young and Zimmie, 1995c; Moo-Young and Zimmie, 1996; Zimmie and Moo-Young, 1995; Zimmie et al., 1993; Floess et al., 1995). In spite of high water contents and low solids contents in comparison to clays, some paper mill sludges can achieve low hydraulic conductivities comparable to clays used in landfill covers. Moreover, since paper mill sludges are a waste product, they are generally provided to the landfill owner at little or no cost, reducing the cost of cap construction (Moo-Young, 1995).

Paper mill sludges have been used to cap landfills in Wisconsin since 1975 (Stoffel and Ham, 1979; Pepin, 1985). In 1984, the National Council of the Paper Industry for Air and Stream Improvement, Inc., (NCASI) began a comprehensive investigation of the potential use of paper mill sludge for hydraulic barrier material in landfill caps (NCASI, 1989; NCASI, 1990). This investigation included a summary of unpublished industry experience with alternative cover systems, indicating that paper mill sludge was used as the hydraulic barrier in the final cover of five landfills (NCASI, 1989). Four of these were industrial landfills; the other was a municipal landfill. Only one of the cover systems had a hydraulic conductivity criterion of 1×10^{-7} cm/s or less. The investigation also included a laboratory study to physically and chemically characterize paper mill waste materials. Measured hydraulic conductivities were variable, ranging between 10^{-4} and 10^{-8} cm/s. Hydraulic conductivities were observed to decrease with time. This decrease was attributed to consolidation of test specimens under applied loads.

NCASI constructed four test pads in 1987 to evaluate the performance of paper sludge as a hydraulic barrier in landfill caps (NCASI, 1990). Two cells were constructed using paper sludge barrier layers; the other two cells were constructed with clay barrier layers to provide a baseline. Provisions were made for collecting and monitoring runoff and run-through. Conclusions derived from the test pads are:

- The sludge consolidated as much as about 30 percent, with most consolidation occurring during the first year.
- Measured runoff from the sludge test pads was similar to that from the clay test pads during the first year. Thereafter, runoff from the sludge test pads exceeded runoff from the clay test pads.
- After the first year, measured run-through in the sludge test pads was less than the run-through in the clay test pads.
- Combined sludge from primary and secondary treatment performed better than did sludge from only primary treatment.

Data from the NCASI test pads are also summarized by Kraus, et al, (1997), who conclude that the hydraulic conductivity of paper mill sludge remains the same or decreases slowly during long term permeation.

Beginning in the late 1980's, Erving Paper Mill, Erving, MA, conducted a comprehensive study on the use of their sludge as barrier layer material in landfill caps (Aloisi and Atkinson, 1991). Six test plots were constructed to evaluate the performance of Erving Paper Mill's sludge as hydraulic barrier in landfill caps. Both primary and combined sludges were evaluated. One of the test pads was constructed with clay as a control. The test pads included provisions for monitoring and collecting runoff and run-through. Conclusions derived from the test pads include:

- The hydraulic conductivity of the sludge decreased with time. The measured hydraulic conductivity of the combined sludge decreased by about one order of magnitude. The measured hydraulic conductivity of the primary sludge decreased to about one-third of its initial value. The presence of fine colloidal material in the secondary sludge was used to explain the better performance of combined sludge.
- The clay test pad showed significant deterioration due to freezing and thawing. The sludge, however, showed improved performance over the first winter.

Based on the results of the test plots, the Massachusetts Department of Environmental Protection (MADEP) approved in 1991 a full scale demonstration project using Erving Paper sludge as barrier layer material at the 1.8 ha (4.5 acre) Hubbardston, MA, municipal landfill (Aloisi and Atkinson, 1991; Floess et al, 1995). The paper sludge barrier layer was thickened to 0.9 m (36 inches) in lieu of the standard 0.45 m (18 inches) of clay. The sludge was placed and compacted using low pressure tracked dozers. A paper mill roller was used for compaction and to smooth the sludge surface. The paper sludge barrier was covered with 0.15m (6 inches) of sand and 0.30m (12 inches) of vegetative-support soil.

Laboratory hydraulic conductivity testing of sludge shelby tube samples obtained shortly after completion of the barrier layer indicated variable hydraulic conductivities, averaging about 3 x 10^{-7} cm/s. Sampling and testing of sludge samples performed nearly two years after completion of the cap indicated an average hydraulic conductivity of 4 x 10^{-8} cm/s, a decrease of about one order of magnitude. This is comparable to the performance of the test pads.

Erving Paper Mill sludge was also used to cap the Town of Marlborough, New Hampshire, municipal landfill (Floess et al, 1995). This was the first use of paper sludge as barrier layer material in New Hampshire. Cap construction was completed in 1994.

In addition to use as barrier layer material, paper sludge has been used as a topsoil amendment in landfill caps (Floess et al, 1995).

IP SLUDGE

Hudson River Mill produces about 185,000 tons of coated groundwood and free sheet publication papers annually. These products are used in magazines, mail order catalogues, textbooks, trade journals, and advertising pieces. The mill has been involved in paper making for over a century and was one of the original 20 northeastern mills that joined to form the International Paper Co. in 1898. It is the only one of the original mills still operated by IP. The mill added an off-machine coater in 1941 and has produced coated papers since that time. Since 1960, the mill has used its own mechanically ground wood, purchased hard and soft wood pulp, and clay based coating in its paper making process.

A wastewater treatment plant was constructed in 1972. The mill's wastewater flows to two primary clarifiers to remove suspended solids. A trickling filter is then used to biologically treat the wastewater. Secondary clarifiers remove the organics generated from biological treatment. Primary (90%) and secondary (10%) sludge is combined, and a screw press is used to dewater the sludge. The resulting sludge is composed primarily of wood fibers and kaolin clay, and has consistently been about 50% clay and 50% wood fibers for more than 30 years. The sludge has been stockpiled in a sludge landfill since about 1973.

GEOTECHNICAL PROPERTIES

The geotechnical characteristics of paper mill sludges differ considerably from a typical clay used as the barrier layer of a landfill cover system. For example, paper mill sludges are highly compressible and have high initial water contents (100 to 300%) compared to a typical clay (30%). Paper mill sludges display geotechnical behavior similar to peats and highly organic soils.

A series of laboratory tests were performed on three IP sludge samples to evaluate the sludge's physical properties for the feasibility study. All sludge samples were taken from the surface of the mill's landfill. Both new and older sludge were tested to evaluate whether the sludge's physical properties change with time. New sludge was about 1 week old (sample IP1). Two older sludge samples were estimated to be about 2 to 4 years old (sample IP2) and 10 to 14 years old (sample IP3). Test data are summarized on Table 1.

TABLE 1
SUMMARY OF LABORATORY TEST DATA
IP SLUDGE - FEASIBILITY STUDY

Sludge Sample	Water Content (%)	Organic Content (%)	Specific Gravity	Hydraulic conductivity (cm/s)
IP1	255-268	54-56	1.80-1.84	1 x 10^{-6} - 7 x 10^{-7}
IP2	183-198	47-49	1.90-1.93	2 x 10^{-7} - 1 x 10^{-7}
IP3	222-231	42-46	1.96-1.97	2 x 10^{-7} - 6 x 10^{-8}

Notes:

1. Sample IP1 - New sludge
   Sample IP2 - 2 to 4 years old
   Sample IP3 - 10 to 14 years old

2. Hydraulic conductivity tests were performed at confining pressures of 34.5 kPa (5 psi) to 69 kPa (10 psi)

Water Content

Water content was determined according to American Society for Testing and Materials (ASTM) D 2974, except that the oven temperature was lowered from 105°C to 70°C to avoid burning off some of the organics (Goodman and Lee, 1962; MacFarlane and Allen, 1964; Raghu et al., 1987; Alvi and Lewis, 1987). A large sample of sludge is required to obtain an accurate measurement of water content. Two to three days were required to completely dry the specimen. The initial (natural) water contents of the IP sludge samples analyzed for this study ranged from about 190 to 260 percent. This corresponds to a solids content of 0.28 to 0.34, defined as the ratio of dry solids to total weight. Although the sludge visually appears damp, water can readily be squeezed from it under hand pressure.

Organic Content

Organic content tests were performed according to ASTM D 2974, method C, for geotechnical classification. A muffle furnace was used to burn off the organics at a temperature of 440°C. Sludges with greater organic contents tend to have higher water contents and void ratios, and will be more compressible. This relationship is also true for peats (MacFarlane, 1969a and 1969b).

Measured organic contents were found to decrease from about 55 percent for new sludge to about 44 percent for the 10 to 14 year old sludge. This decrease in organic content is attributed to biological decomposition of the organic fibers and tissue in the sludge over time (Moo-Young, 1995).

Specific Gravity

Specific gravity tests were performed according to ASTM D 854. Slight modifications were made to apply the procedure to paper sludge. An aspirator was used to remove entrapped air from the sample, and boiling was avoided. The sludge specimens were taken at their natural water content and soaked in water for an hour before pulverization, since upon drying, the sludge samples formed flocs, developed a coarse texture, and were not easily pulverized. This behavior was noted by Wang et al (1991) for a water plant sludge and by Feustel and Byers (1930) for various peat types.

Measured specific gravities range from about 1.82 for new sludge to about 1.96 for the oldest sludge. The data indicate a direct relationship between specific gravity and organic content. In general, paper sludges with lower percentages of organics have higher percentages of clay. Since clay has a specific gravity of about 2.70 and the fibers are estimated to have a specific gravity of about 1.5, the average specific gravity can be estimated from the equation (Charlie, 1977):

$$G = 1.5O_c + 2.7\,(1-O_c) \qquad (1)$$

where, G – Specific Gravity
O_c = Organic Content

Peat soils show similar trends (MacFarlane, 1969b).

Compressibility

One dimensional consolidation tests were performed following ASTM D 2435, methods A and B. Figure 1 shows the plot of strain versus the logarithm of pressure from a typical consolidation test on IP sludge. The tests confirm that the sludge is highly compressible, with strains of about 65 percent at the final loading of 1532kPa. Paper sludge is also characterized by high rates of secondary compression, similar to peat soils.

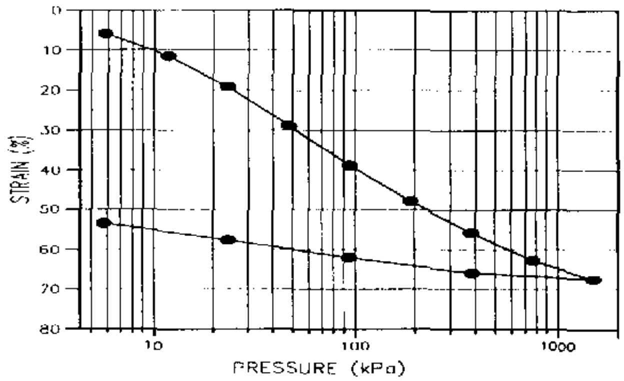

Figure 1. Typical Consolidation Test Results for IP Sludge

Consolidation tests were performed on the IP sludge samples at their initial water content. Measured compression indices (C_c) range between 1.4 and 1.7; measured compression ratios range between about 0.29 and 0.36. The relationship between the compression index, C_c, and initial water content, w_o(%), for peat soils has been found to vary between $C_c = 0.0075w_o$ and $C_c = 0.011\,w_o$ (McFarlane, 1969b). The relationship between the compression index, C_c, and initial void ratio, e_o, for peats has been found to range between $C_c = 0.45e_o$ and $C_c = 0.75e_o$. Test data for IP sludge fall within these ranges.

The organic content of sludge can also be used as an indicator of the sludge's compressibility. The measured relationship between the compression index, C_c, and organic content, O_c (%), for IP sludge is approximately:

$$C_c = 0.033\,O_c \qquad (2)$$

The consolidation tests indicate that a low permeability paper sludge barrier layer would experience significant compression, even under the low overburden pressure in a landfill cap, amounting to 15 to 25 percent strain. The barrier layer, therefore, should be thickened to account for this large anticipated compression. Because paper sludge is highly compressible, its physical properties will change with time in a cap as the sludge gradually compresses. In particular, the sludge's void ratio, water content, and hydraulic conductivity will change with time. This is not normally a consideration with clay caps, since the compression of a typical clay barrier layer would be negligible.

Hydraulic Conductivity

A flexible wall permeameter was used to determine the one dimensional hydraulic conductivity of paper sludge samples following the ASTM procedure D 5084. The data indicate that the hydraulic conductivity of the IP sludge decreases with age. The new sludge had the highest hydraulic conductivity, generally in excess of 1 x 10^{-7} cm/s. In comparison, the 10 to 14 year old sludge had measured hydraulic conductivities ranging from somewhat more than 1×10^{-7} cm/s to less than 1×10^{-8} cm/s.

The decrease in hydraulic conductivity with age appears to be related to a decrease in organic content and resulting more clayey sludge. This has important practical implications relative to landfill cover design since biodegradation will result in a lower organic content and consequent decrease in hydraulic conductivity.

The hydraulic conductivity of IP paper sludge was found to be approximately:

$$k = 10^{(0.07O_c - 10)} \tag{3}$$

where, k = hydraulic conductivity, cm/s
O_c = organic content, percent

This relationship also appears valid for other paper sludges.

Paper sludge is highly compressible and undergoes a large reduction in water content and void ratio as it is loaded. Compression and change in void ratio continue for some time due to high rates of secondary compression. This compression directly affects the hydraulic conductivity of the paper sludge. Sludge sample IP3 showed a decrease in hydraulic conductivity of about two orders of magnitude as the confining pressure increased to 250kPa (36 psi) (Moo-Young, 1995). Similar results were reported for peat soils by Cedergren (1989), Hanrahan (1954) and Lea & Brawner (1963).

The decrease in hydraulic conductivity of a typical landfill clay barrier between the time of initial placement and the end of consolidation is relatively minor because there is little change in void ratio due to the low effective stresses caused by the cover soils. However, because paper sludge is highly compressible, its hydraulic conductivity will decrease substantially as the sludge consolidates and undergoes secondary compression.

Freeze Thaw Effects

Remolded sludge IP3 specimens were subjected to one dimensional freezing and thawing at a water content of 175%. Specimens were compacted into 10.2 cm high by 7.6 cm diameter PVC molds in three equal lifts, using six blows of a standard Proctor compaction hammer. Specimens were sealed in plastic wrap and taped to prevent moisture loss. The one dimensional freeze/thaw process used in this study has been previously described by Zimmie and LaPlante (1990). Hydraulic conductivity tests were conducted on frozen sludge specimens after 0, 1, 3, 5, and 8 freeze/thaw cycles.

Hydraulic conductivity testing followed ASTM procedure D5084 with backpressure application. Specimens were permeated under an effective stress of 34.5, 69, and 138 kPa (5, 10, and 20 psi), using a low hydraulic gradient. The permeation phases of the tests were generally conducted for two to three days.

Hydraulic conductivity tests are summarized on Figure 2. A one to two orders of magnitude increase in hydraulic conductivity occurs within eight freeze/thaw cycles at the various cell pressures.

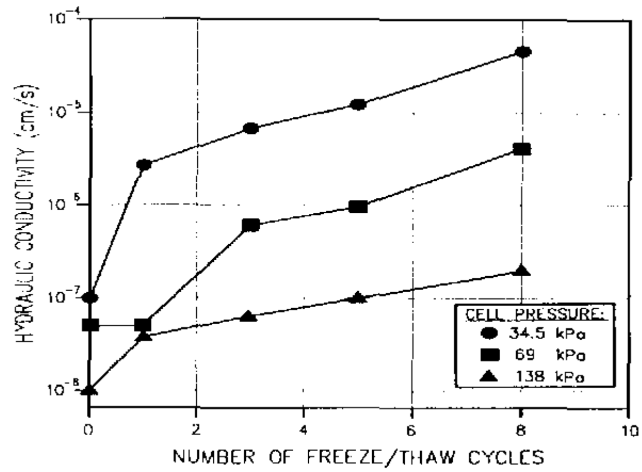

Fig. 2. Number of Freeze/Thaw Cycles versus Hydraulic Conductivity for Sludge IP3

Extensive research has been conducted on the effects of freezing and thawing on fine grained soils. In general, compacted clays increase in hydraulic conductivity by one to three orders of magnitude (Othman et al., 1995).

Shear Strength

A series of three consolidated-undrained (CIU) triaxial compression tests with pore pressure measurements performed on the 10 to 14 year old sludge indicates that the material has an angle of internal friction of about 32° and a small cohesion intercept of about 9 kPa (1.3 psi). Similar results were found by Charlie (1977), who reported that the friction angle of paper sludge increases with increasing organic content. Charlie (1977) also observed that the presence of fibers in the sludge should help to reinforce it and retard the propagation of a failure zone.

CENTRIFUGE TESTING

Centrifuge model tests were performed on test pads of landfill barrier layer material using Rensselaer Polytechnic Institute's 100 g-ton centrifuge. The primary purpose of the tests was to simulate infiltration through the paper sludge cap over a 30 year period. Centrifuge modeling was done in lieu of field test sections, at a significant savings in time and cost. The models were constructed and tested over a period of several weeks. Field test sections would have required a year or more to construct and evaluate.

In centrifuge testing, time is scaled as the square of gravitational acceleration. The 30-year prototype period was scaled to about 24 hours at 105g acceleration in the centrifuge model (Zimmie et al, 1995).

Three model tests were performed: two using paper sludge and one using clay for comparison. To simulate rainfall, water was added to the top of the model before starting the test and in-flight. Resulting run through was collected for analytical testing. Both compression and pore pressure in the barrier layer were also monitored during the tests (Zimmie et al, 1994).

CAP DESIGN

The cap design for the Corinth Landfill closure took into consideration the unique physical characteristics of the sludge material. Because paper sludge is highly compressible, the barrier layer was thickened from the normal 0.45 meters (18 inches) to 0.76 meters (30 inches). Research indicated that the hydraulic conductivity of the paper sludge increases as a result of freeze-thaw cycles; therefore a frost protection layer of 0.45 meters (18 inches) of additional paper sludge was included in the cap. Paper sludge, because of its high water content, provides excellent frost protection.

The cap system included the following components:

- 0.76m (30") Barrier protection layer and topsoil (sand)
- 0.45m (18") Frost protection layer (paper sludge)
- 0.76m (30") Barrier layer (paper sludge)
- 0.30m (12") Gas venting layer (sand)

In order to provide a barrier layer with the lowest hydraulic conductivity, old sludge excavated from IP's sludge landfill was used for the barrier layer. New sludge was used for the frost protection layer since the hydraulic conductivity of this layer was not an issue.

Since it was anticipated that the hydraulic conductivity of the paper sludge will decrease with time due to consolidation and secondary compression, NYSDEC agreed to a criterion of 5×10^{-7} cm/s for acceptable hydraulic conductivity of the barrier layer sludge immediately after placement.

A perimeter collection trench was included in the cap design. The intent was to collect runoff from the top of the barrier layer; that is, water that had percolated through the barrier protection layer and onto the surface of the barrier layer. Runoff from the upper surface of the cap was not collected. Manholes were provided to sample the collected runoff for analytical testing.

CAP CONSTRUCTION

The Corinth Landfill was capped in 1993-1994 by Town forces. About 4.1 ha (10 acres) of the landfill received a paper sludge cap; the remaining 1.2 ha (3 acres) received a conventional clay cap as a control section. To construct the paper sludge barrier layer, Town crews spread the sludge in approximately 0.25 meter (10 inch) lifts using a small dozer. Each lift was then rolled to eliminate voids between clods and to smooth the surface, using a paper mill roller pulled by a dozer or other tracked vehicle, Figure 3. The Town primarily used a snow-mobile grooming machine for this purpose.

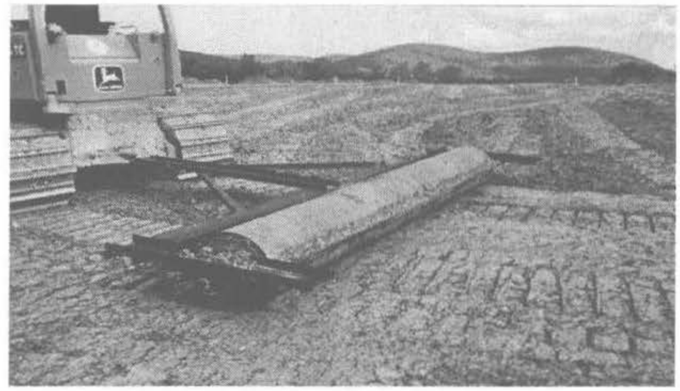

Fig. 3. Cap Construction

The paper sludge was placed and rolled at its natural water content, without moisture conditioning. Moisture contents of about 150 to 250 percent (29 to 40 percent solids) were found to be ideal for placing and spreading sludge. Drier sludge tended to maintain the features of individual clods after rolling. Wetter sludge tended to be soft and unworkable.

Provided the sludge was rolled smooth, it readily shed water and did not dry out easily and did not develop shrinkage cracks or become dusty like clay. Cap construction with paper sludge proceeded under a broader range of weather conditions than normal clay cap construction could have.

The Town Highway Superintendent found paper sludge easy to work with, with cap construction much simpler than clay cap construction.

QA/QC

QA/QC testing during construction included hydraulic conductivity tests on shelby tube and remolded samples, plus measurement of water content, organic content, and specific gravity. In place density testing was not performed, since rolling was intended to knead clods into a homogeneous mass and to smooth the surface, rather than achieve a specified density.

A total of 30 shelby tube samples were obtained from the paper sludge barrier layer. Measured organic contents varied from 32 to 52 percent, averaging about 45 percent. Measured specific gravities ranged from 1.81 to 2.26, averaging about 2.0. Natural water contents of the sludge used to construct the barrier layer ranged from about 100 to 170 percent, averaging about 150 percent. These water contents are significantly lower than the water contents of the samples tested for the feasibility study.

This is apparently the result of previous consolidation within the sludge landfill from which the material was mined. Samples for the feasibility study were obtained from the sludge landfill surface and had not undergone consolidation due to the weight of overlying sludge.

Measured hydraulic conductivities ranged from $2x10^{-6}$ to $2x10^{-8}$ cm/s, averaging about $4x10^{-7}$ cm/s. The relationship between measured hydraulic conductivity and organic content is presented in Figure 4.

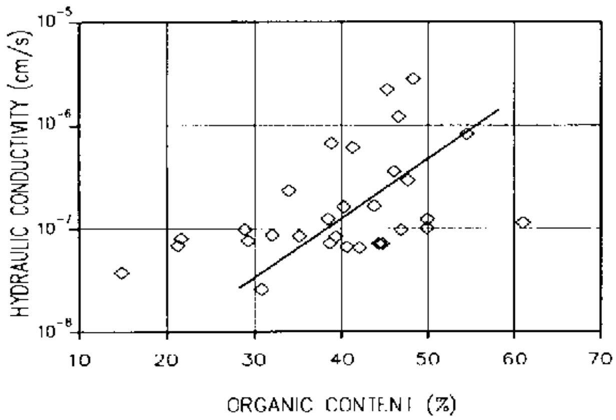

Fig. 4. Hydraulic Conductivity versus Organic Content for IP Sludge Barrier Layer

SUMMARY AND CONCLUSIONS

1. Paper sludge has been successfully used as the barrier layer to cap the Corinth, NY, municipal landfill.

2. Paper sludge has a high water content and is highly compressible. It behaves similar to highly organic peat soils.

3. The hydraulic conductivity of paper sludge decreases as the organic content decreases. To achieve a hydraulic conductivity less than 1×10^{-7} cm/s, paper sludge should have an organic content less than about 50 percent. As the paper sludge biodegrades with age, its hydraulic conductivity should decrease.

4. Freeze-thaw cycles tend to increase the hydraulic conductivity of IP paper sludge by one to two orders of magnitude.

5. Because it is highly compressible, the paper sludge barrier layer was thickened from the normal 0.45m (18") to 0.76m (30"). The barrier layer was also protected from frost action.

6. Paper sludge was placed and rolled at its natural water content. The sludge was compacted using a paper mill roller to eliminate voids between clods and smooth the surface.

7. QA/QC testing during construction included hydraulic conductivity tests of shelby tube samples plus measurement of water content, organic content, and specific gravity. The average water content was about 150 percent; the average organic content was about 45 percent; and the average specific gravity was about 2.0. The average measured hydraulic conductivity was about 4×10^{-7} cm/s.

8. Paper sludges vary from mill to mill. Each sludge material needs to be evaluated to determine its suitability for cap material. Relationships are suggested herein to estimate hydraulic conductivity and compressibility of paper sludge based on simple index parameters, such as water content and organic content. The chemical characteristics of the sludge also need to be evaluated.

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